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## COFIBRATIONS IN THE CATEGORY OF NONCOMMUTATIVE CW COMPLEXES

V. MILANI, S. M. H. MANSOURBEIGI AND A.-A. REZAEI

**ABSTRACT.** Cofibration in the category of noncommutative CW complexes is defined. The  $C^*$ -algebraic counterparts of topological mapping Cylinder and mapping cone are presented as examples of noncommutative CW complex cofibres. As a generalization, the concepts of noncommutative mapping cylindrical and conical telescope are introduced to provide more examples of noncommutative CW complex cofibres. Their properties and K-theoretic behavior are also studied in detail. It is seen that they carry the properties similar to the topological properties of their CW complex counterparts.

### 1. INTRODUCTION

The category of  $C^*$ -algebras and  $*$ -homomorphisms can be interpreted as the noncommutative counterpart of the category of topological spaces and continuous maps [1, 2, 8]. Its origin goes back to the Gelfand duality. The results of the paper [7] known as the Gelfand-Naimark theorem provide a duality between the topology of locally compact spaces and the algebraic structure of commutative  $C^*$ -algebras. The duality creates a dictionary between the two categories. Topological constructions such as cofibrations, mapping cylinder and mapping cone are translated into their  $C^*$ -algebraic counterparts [12, 13]. In the absence of commutativity, the dictionary may still contain noncommutative CW complexes (NCCW complexes) as the  $C^*$ -algebraic version of the topological CW complexes defined in [6]. The noncommutativity comes from the fact that noncommutative CW complexes are algebras of matrix-valued continuous functions. In [11], we studied some of the geometric properties of noncommutative CW complexes. In this paper, we are motivated by noncommutative constructions through NCCW complex examples and study their topological properties. In this regard the paper is organized as follows.

Section 2 is a review of basic tools: extensions, pullbacks, NCCW complexes and their primary properties. Section 3 is devoted to the study of cofibrations and cofibres in the category of NCCW complexes. In this section we explain the  $C^*$ -algebraic counterparts of the topological mapping cylinder and mapping cone.

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We apply the pull back point of view of Pedersen [12] to the class of NCCW complexes. We show that the C\*-algebraic mapping cylinder and mapping cone defined in [13] are obtained through the pull back constructions and are examples of NCCW complexes. We also calculate their dimensions. Our approach is different from that of Diep in [3, 4, 5] who defined the noncommutative mapping cylinder and cone in a different way as NCCW complexes. The key concept of this section is the construction of examples for NCCW complex cofibrations and cofibres. In Section 4, we generalize the concepts of the previous section to provide more examples of NCCW complex cofibres and introduce noncommutative mapping cylindrical and conical telescope. Their properties and K-theoretic behavior are also studied in detail. We will see that they carry the properties similar to the topological properties of their CW complex counterparts.

All throughout the paper  $\mathcal{C}_{\text{alg}}^*$  is the category of C\*-algebras and \*-homomorphisms as morphisms. The kernel of a morphism  $\varphi: A \rightarrow B$  in this category is the embedding  $\ker \varphi \rightarrow A$ . We also use Pedersen abbreviation [12] “NCCW complexes” for noncommutative CW complexes. The category of topological spaces and continuous maps is denoted by **Top**.

## 2. BACKGROUND

The notion of NCCW complexes was first introduced by Pedersen et al [6]. They are in fact the C\*-algebraic counterpart of topological CW complexes. We discuss the category of noncommutative CW complexes from [6] and refer to [9] for details on topological CW complexes. First we review basic tools of pullbacks from [10, 12].

*Notation.* The following notations are used throughout this paper.

$$\mathbb{I} = [0, 1], \quad \mathbb{I}^n = [0, 1]^n, \quad \mathbb{I}_0^n = (0, 1)^n.$$

For a C\*-algebra  $A$  and a compact space  $X$ ,  $XA = C(X \rightarrow A)$  is the C\*-algebra of continuous functions on  $X$  with values in  $A$ , and if  $X$  is locally compact,  $C_0(X \rightarrow A)$  is the C\*-algebra of continuous functions on  $X$  vanishing at infinity. Also we denote  $C(X \rightarrow \mathbb{C})$  by  $C(X)$  and

$$\begin{aligned} \mathbb{I}A &= C(\mathbb{I} \rightarrow A), & \mathbb{I}^n A &= C(\mathbb{I}^n \rightarrow A) \\ \mathbb{I}_0^n A &= C_0(\mathbb{I}_0^n \rightarrow A), & S^n A &= C(S^n \rightarrow A). \end{aligned}$$

Here  $\mathbb{I}^{n+1} \setminus \mathbb{I}_0^{n+1}$  is identified with the unit sphere  $S^n$ .

(All the above sets together with the usual pointwise operations, and supremum norm are C\*-algebras).

**Definition 2.1.** For a C\*-algebra  $A$  and for  $t \in \mathbb{I}$ , the morphism

$$ev(t): \mathbb{I}A \rightarrow A, \quad ev(t)f := f(t)$$

is called the evaluation map.

**Definition 2.2** ([8]). Two morphisms  $\alpha, \beta: A \rightarrow B$  are said to be homotopic if there exists a morphism  $H: A \rightarrow \mathbb{I}B$  called homotopy such that  $ev(1)H = \alpha$

and  $ev(0)H = \beta$ .  $A$  is a retraction of  $B$  if there are morphisms  $i: A \rightarrow B$  and  $r: B \rightarrow A$  such that  $ri = \text{id}_A$  and  $ir$  is homotopic to the  $\text{id}_B$ . The  $C^*$ -algebra  $A$  is contractible if its identity map  $\text{id}_A$  is homotopic to the zero map.

**Definition 2.3** ([10, 12]). Let  $A$  and  $C$  be two  $C^*$ -algebras. An *extension* for  $A$  with respect to  $C$  is a  $C^*$ -algebra  $B$  together with two morphisms  $\alpha$  and  $\beta$  for which the following sequence is exact

$$0 \longrightarrow A \xrightarrow{\alpha} B \xrightarrow{\beta} C \longrightarrow 0.$$

**Definition 2.4** ([10, 12]). A *pull-back* for the  $C^*$ -algebra  $C$  via morphisms  $\alpha_1: A_1 \rightarrow C$  and  $\alpha_2: A_2 \rightarrow C$  is the  $C^*$ -subalgebra  $PB$  of  $A_1 \oplus A_2$  defined by

$$PB := \{a_1 \oplus a_2 \in A_1 \oplus A_2 : \alpha_1(a_1) = \alpha_2(a_2)\}.$$

From now on the pull-back decomposition, notation  $PB := A_1 \bigoplus_C A_2$  is used all throughout this paper.

*Remark 2.5.* Since  $\alpha_1$  and  $\alpha_2$  are continuous maps,  $PB$  is closed in  $A_1 \oplus A_2$ , and so it is a  $C^*$ -subalgebra.

*Remark 2.6.* It follows from the definition that the pull-back satisfies the following universality properties:

- It commutes the following diagram

$$\begin{array}{ccc} PB & \xrightarrow{\pi_2} & A_2 \\ \pi_1 \downarrow & & \downarrow \alpha_2 \\ A_1 & \xrightarrow{\alpha_1} & C \end{array}$$

( $\pi_1$  and  $\pi_2$  are projections onto the first and second coordinates).

- For any  $C^*$ -algebra  $D$  and any two  $C^*$ -morphisms  $\delta_1: D \rightarrow A_1$  and  $\delta_2: D \rightarrow A_2$  satisfying the following commutative diagram

$$\begin{array}{ccc} D & \xrightarrow{\delta_2} & A_2 \\ \delta_1 \downarrow & & \downarrow \alpha_2 \\ A_1 & \xrightarrow{\alpha_1} & C \end{array}$$

there exists a unique  $C^*$ -morphism  $\Delta: D \rightarrow PB$  which commutes the diagram

$$\begin{array}{ccccc} D & & & & \\ \delta_1 \swarrow & \Delta \searrow & \delta_2 \searrow & & \\ & PB & \xrightarrow{\pi_2} & A_2 & \\ & \downarrow \pi_1 & & \downarrow \alpha_2 & \\ & A_1 & \xrightarrow{\alpha_1} & C & \end{array}$$

**Definition 2.7** ([6]). The *noncommutative CW complexes* are defined by induction on their dimension as follows.

A NCCW complex of dimension zero is defined to be a finite linear dimensional C\*-algebra  $A_0$  corresponding to the decomposition  $A_0 = \bigoplus_k M_{n(k)}$  of finite dimensional matrix algebras.

In dimension  $n$ , a NCCW complex is defined as a sequence of C\*-algebras  $\{A_0, A_1, \dots, A_n\}$ , where each  $A_k$  is obtained inductively from the previous one by the following pullback construction

$$\begin{array}{ccccccc} 0 & \longrightarrow & \mathbb{I}_0^k F_k & \longrightarrow & A_k & \xrightarrow{\pi} & A_{k-1} \longrightarrow 0 \\ & & \parallel & & \downarrow \rho_k & & \downarrow \sigma_k \\ 0 & \longrightarrow & \mathbb{I}_0^k F_k & \longrightarrow & \mathbb{I}_0^k F_k & \xrightarrow{\partial} & S^{k-1} F_k \longrightarrow 0. \end{array}$$

In the above diagram, the rows are extensions,  $F_k$  is some C\*-algebra of finite dimension,  $\partial$  – the boundary map – is the restriction morphism,  $\sigma_k$  the connecting morphism can be any morphism, and finally,  $\rho_k$  and  $\pi$  are projections onto the first and second factors in the pullback decomposition

$$A_k = \mathbb{I}_0^k F_k \bigoplus_{S^{k-1} F_k} A_{k-1}.$$

*Example 2.8.*  $C(\mathbb{I})$  is a 1-dimensional NCCW complex. To see this, let  $F_1 = \mathbb{C}$ ,  $A_0 = \mathbb{C} \oplus \mathbb{C}$  and  $A_1 = C(\mathbb{I})$ , then we have  $\mathbb{I}_0^1 F_1 = C_0((0, 1))$ ,  $\mathbb{I}^1 F_1 = C(\mathbb{I})$ , and  $S^0 F_1 = \mathbb{C} \oplus \mathbb{C}$ . The pullback construction diagram becomes

$$\begin{array}{ccccccc} 0 & \longrightarrow & C_0((0, 1)) & \longrightarrow & C(\mathbb{I}) & \xrightarrow{\pi} & \mathbb{C} \oplus \mathbb{C} \longrightarrow 0 \\ & & \parallel & & \downarrow \rho_1 & & \downarrow \\ 0 & \longrightarrow & C_0((0, 1)) & \longrightarrow & C(\mathbb{I}) & \xrightarrow{\partial} & \mathbb{C} \oplus \mathbb{C} \longrightarrow 0. \end{array}$$

where  $C(\mathbb{I})$  is identified with

$$\begin{aligned} C(\mathbb{I}) &\simeq \{f \oplus (\lambda \oplus \mu) \in C(\mathbb{I}) \oplus (\mathbb{C} \oplus \mathbb{C}) : f(0) = \lambda, f(1) = \mu\} \\ &= C(\mathbb{I}) \bigoplus_{\mathbb{C} \oplus \mathbb{C}} (\mathbb{C} \oplus \mathbb{C}). \end{aligned}$$

For each  $f \in C(\mathbb{I})$  and  $\lambda, \mu \in \mathbb{C}$ ,

$$\begin{aligned} \pi(f \oplus (\lambda \oplus \mu)) &= \lambda \oplus \mu \\ \rho_1(f \oplus (\lambda \oplus \mu)) &= f \\ \partial f &= f(0) \oplus f(1). \end{aligned}$$

Now the sequence  $\{A_0 = \mathbb{C} \oplus \mathbb{C}, A_1 = C(\mathbb{I})\}$  makes  $C(\mathbb{I})$  into a 1-dimensional NCCW complex. In a similar way we can see that both  $C_0((0, 1])$  and  $C_0((0, 1))$  are 1-dimensional NCCW complexes. We go back to this construction from a different point of view in the following sections.

*Remark 2.9 ([12]).* It follows from the definition of NCCW complexes that for each  $n$ -dimensional NCCW complex  $A_n$ , a decreasing family of closed ideals, called canonical ideals, corresponds

$$A_n = I_0 \supset I_1 \supset \cdots \supset I_{n-1} \supset I_n \neq 0,$$

where  $I_n = \mathbb{I}_0^n F_n$  and for each  $k \geq 1$ ,  $I_k/I_{k+1} = \mathbb{I}_0^k F_k$ . Moreover, for each  $0 \leq k \leq n-1$ ,  $A_n/I_{k+1}$  is a  $k$ -dimensional NCCW complex.

*Example 2.10.* For the NCCW complex of  $C(\mathbb{I})$ , the canonical ideals are

$$C(\mathbb{I}) = I_0 \supset I_1 = \mathbb{I}_0^1 F_1 = C_0((0, 1)).$$

The noncommutative analog of simplicial maps between CW complexes are defined as follows.

**Definition 2.11 ([6]).** A *simplicial morphism* from the  $n$ -dimensional NCCW complex  $A_n$  into the  $m$ -dimensional NCCW complex  $B_m$  is a mapping  $\alpha: A_n \rightarrow B_m$  satisfying the following two conditions:

- If

$$\begin{aligned} A_n &= I_0 \supset I_1 \supset \cdots \supset I_{n-1} \supset I_n \neq 0 \\ B_m &= J_0 \supset J_1 \supset \cdots \supset J_{m-1} \supset J_m \neq 0 \end{aligned}$$

are the sequences of canonical ideals for  $A_n$  and  $B_m$ , then  $\alpha(I_k) \subset J_k$  for all  $k$ . Particularly  $\alpha(I_k) = 0$  for  $k > m$ .

- For  $0 \leq k \leq n$ , if  $I_k/I_{k-1} = \mathbb{I}_0^k F_k$ ,  $J_k/J_{k-1} = \mathbb{I}_0^k G_k$  and  $\tilde{\alpha}_k: \mathbb{I}_0^k F_k \rightarrow \mathbb{I}_0^k G_k$  is the homomorphism induced by  $\alpha$ , then there exist a morphism  $\varphi_k: F_k \rightarrow G_k$  and a homeomorphism  $i_k$  of  $\mathbb{I}_0^k$  such that  $\tilde{\alpha}_k = i_k^* \otimes \varphi_k$ , where  $i_k^*: C_0(\mathbb{I}_0^k) \rightarrow C_0(\mathbb{I}_0^k)$  is induced by  $i_k$ . Here  $\mathbb{I}_0^k F_k$  is identified with  $C_0(\mathbb{I}_0^k) \otimes F_k$  and the same for  $\mathbb{I}_0^k G_k$ .

The category of NCCW complexes and simplicial morphisms is denoted by  $\mathcal{C}_{nccw}$ .

*Remark 2.12.* Some facts on simplicial morphisms are stated here. For more details on the proof, see [12].

1. The kernel and the image of a simplicial morphism are NCCW complexes.
2. The pullback of a NCCW complex  $C$  via simplicial morphisms  $\alpha: A_n \rightarrow C$  and  $\beta: B_m \rightarrow C$  is a NCCW complex of dimension  $\max\{n, m\}$ .
3. If  $A_n$  and  $B_m$  are NCCW complexes of dimensions  $n, m$ , respectively, then their tensor product  $A_n \otimes B_m$  is a NCCW complex of dimension  $n + m$ . Moreover, for each  $k \leq n$ ,  $l \leq m$ , the quotient morphism

$$A_n \otimes B_m \rightarrow A_k \otimes B_l$$

onto the tensor product of subcomplexes is a simplicial morphism.

### 3. COFIBRATIONS IN THE CATEGORY NCCW COMPLEXES

In this section, we review the concept of cofibration in the category  $\mathcal{C}_{\text{alg}}^*$  from [13, 14] and modify it to define cofibrations on the category  $\mathcal{C}_{nccw}$ . We see how the  $C^*$ -algebraic mapping cylinder and mapping cone defined in [13] are obtained

through the pull back constructions of [12] and study their relation with cofibrations and cofibres in the category  $\mathcal{C}_{nccw}$ .

The notion of cofibration in the category  $\mathcal{C}_{\text{alg}}^*$  is the  $C^*$ -algebraic translation of the concept of fibration for the category **Top**. It is defined in the following way.

**Definition 3.1** ([13, 14]). A morphism  $f: A \rightarrow B$  in the category  $\mathcal{C}_{\text{alg}}^*$  is called a cofibration if it satisfies the following property.

Given a  $C^*$ -algebra  $D$ , a homotopy  $g: D \rightarrow \mathbb{I}B$  and a morphism  $g_0: D \rightarrow A$  lifting  $g$  at zero, i.e.,  $fg_0(x) = g(x)(0)$ , then there exists a homotopy  $h: D \rightarrow \mathbb{I}A$  lifting  $g$ , i.e.,  $h(x)(0) = g_0(x)$  and  $f(h(x)(t)) = g(x)(t)$  for  $x \in D$ ,  $t \in \mathbb{I}$ .

*Remark 3.2.* A cofibration is surjective [14].

**Definition 3.3.** A cofibration in the category of NCCW complexes  $\mathcal{C}_{nccw}$  is a cofibration in the category  $\mathcal{C}_{\text{alg}}^*$  which is also simplicial. The kernel of a cofibration is called a cofiber.

**Proposition 3.4.** For each NCCW complex  $A$  of dimension  $n$ ,  $\mathbb{I}A$  is a NCCW complex of dimension  $n+1$ . Moreover, the evaluation map  $ev(1): \mathbb{I}A \rightarrow A$  defined by  $f \mapsto f(1)$  is a simplicial morphism and a cofibration (the same is true for  $ev(t_0)$  for each  $t_0 \in \mathbb{I}$ ).

*Proof.*  $\mathbb{I}A$  can be identified with the tensor product  $C(\mathbb{I}) \otimes A$ . So it is a NCCW complex of dimension  $n+1$ .  $A$  is embedded in  $\mathbb{I}A$  and we can regard  $A$  as a NCCW subcomplex of  $\mathbb{I}A$ .  $ev(1)$  (and also  $ev(t_0)$  for each  $t_0 \in \mathbb{I}$ ), is a quotient morphism, and so by the property §3 of remark 2.12, it is simplicial morphism.

To show that it is a cofibration, let  $D$  be a  $C^*$ -algebra and  $G: D \rightarrow \mathbb{I}A$  be a homotopy with a lift  $g_0: D \rightarrow A$  at zero, i.e.,  $(ev(1)g_0)(d) = G(d)(0)$  for  $d \in D$ . Define the homotopy  $H: D \rightarrow \mathbb{I}(\mathbb{I}A)$  by

$$H(d)(t) = f_t$$

for  $d \in D$  and  $t \in \mathbb{I}$ . Let  $g_0(d) = f$ , then  $f(1) = G(d)(0)$ .  $f_t$  must be defined so that

$$\begin{aligned} ev(1)(H(d)(t)) = G(d)(t) &\implies f_t(1) = G(d)(t) \\ H(d)(0) = g_0(d) &\implies f_0 = f. \end{aligned}$$

Set

$$\hat{f}_t(s) = \begin{cases} G(d)(t-2s) & 0 \leq s \leq \frac{t}{2} \\ f\left(\frac{2-2s}{2-t}\right) & \frac{t}{2} \leq s \leq 1. \end{cases}$$

Now set  $f_t(s) = \hat{f}_t(1-s)$ .

In the same way we can see  $ev(t_0)$  is a cofibration.  $\square$

*Example 3.5.*  $C_0((0, 1])$  is a cofiber. To see this, we notice that  $\mathbb{C}$  is a zero dimensional NCCW complex with the only nonzero ideal  $\mathbb{C}$ . Now by Proposition 3.4,  $C(\mathbb{I}) = \mathbb{I}\mathbb{C}$  is a 1-dimensional NCCW complex. Moreover, the evaluation map

$$ev(0): C(\mathbb{I}) \longrightarrow \mathbb{C}, \quad f \longmapsto f(0),$$

is a simplicial cofibration. Its kernel is  $C_0((0, 1])$  which is the cofiber of this cofibration. Also from property §1 of remark 2.12,  $C_0((0, 1])$  is a NCCW complex. Its dimension is one, because it is not of finite linear dimension (and so it is not a 0-dimensional NCCW complex).  $C_0([0, 1])$  being identical to  $C_0((0, 1])$  is a NCCW complex of dimension one. In a similar way,  $C_0((0, 1))$  is the kernel of the simplicial morphism

$$\beta: C_0((0, 1]) \longrightarrow \mathbb{C}, \quad f \longmapsto f(1)$$

and so it is a 1-dimensional NCCW complex cofiber.

**Definition 3.6** ([13]). For a morphism  $\alpha: A \rightarrow B$  in the category  $\mathcal{C}_{\text{alg}}^*$ , the *noncommutative mapping cylinder* is defined by

$$\text{Cyl}(\alpha) := \{a \oplus f \in A \oplus \mathbb{I}B : f(1) = \alpha(a)\}.$$

**Proposition 3.7.** *For an arbitrary morphism  $\alpha: A \rightarrow B$  between  $C^*$ -algebras, the induced morphism  $p: \text{Cyl}(\alpha) \rightarrow B$  defined by  $p(a, f) = f(0)$  for  $(a, f) \in \text{Cyl}(\alpha)$ , is a cofibration in the category  $\mathcal{C}_{\text{alg}}^*$ .*

*Proof.* See [13]. □

**Proposition 3.8.** *If  $A_n$  and  $B_m$  are NCCW complexes of dimensions  $n, m$ , respectively, and if  $\alpha: A_n \rightarrow B_m$  is a simplicial morphism, then  $\text{Cyl}(\alpha)$  is a NCCW complex of dimension  $\max\{n, m + 1\}$ .*

*Proof.*  $\text{Cyl}(\alpha)$  satisfies the following pullback diagram

$$\begin{array}{ccc} \text{Cyl}(\alpha) & \xrightarrow{\pi_2} & \mathbb{I}B_m \\ \pi_1 \downarrow & & \downarrow ev(1) \\ A_n & \xrightarrow{\alpha} & B_m, \end{array}$$

where  $\pi_1$  and  $\pi_2$  are projections onto the first and second coordinates.

$\mathbb{I}B_m$  is a NCCW complex of dimension  $m + 1$ ,  $ev(1)$  and  $\alpha$  are simplicial morphisms in the pullback diagram for  $\text{Cyl}(\alpha)$ . Now it follows from Remark 2.12 that  $\text{Cyl}(\alpha)$  is a NCCW complex of dimension  $\max\{n, m + 1\}$ . □

**Definition 3.9** ([9, 13]). For a  $C^*$ -algebra  $A$ , the *noncommutative cone* over  $A$ ,  $CA$ , and the *noncommutative suspension* of  $A$ ,  $SA$ , respectively, are defined by

$$\begin{aligned} CA &:= \{f \in \mathbb{I}A; f(0) = 0\} \\ SA &:= \{f \in \mathbb{I}A; f(0) = f(1) = 0\}. \end{aligned}$$

*Remark 3.10.* It follows that:

- $SA \subset CA \subset \mathbb{I}A$ .
- $CA$  is contractible.
- $SA$  is contractible only if  $A$  is contractible.

See [15] for details.

**Proposition 3.11.** *For every NCCW complex  $A$  of dimension  $n$ , the cone  $CA$  and the suspension  $SA$  are NCCW complexes of dimension  $n + 1$ .*



*Proof.* This follows from Example 3.5, property §<sub>3</sub> of Remark 2.12, and the following identifications

$$\begin{aligned} CA &= C_0((0, 1] \rightarrow A) \simeq C_0((0, 1]) \otimes A \\ SA &= C_0((0, 1) \rightarrow A) \simeq C_0((0, 1)) \otimes A. \end{aligned}$$

□

**Definition 3.12** ([13]). For a morphism  $\alpha: A \rightarrow B$ , the *noncommutative mapping cone* of  $\alpha$  is defined by

$$\text{Cone}(\alpha) := \{a \oplus f \in A \oplus CB : f(1) = \alpha(a)\}.$$

**Proposition 3.13.** *If  $\alpha: A_n \rightarrow B_m$  is a morphism between NCCW complexes of dimension  $n$  and  $m$ , then  $\text{Cone}(\alpha)$  is a cofiber in the category  $\mathcal{C}_{\text{nccw}}$ . Moreover, if  $\alpha$  is a simplicial morphism, then  $\text{Cone}(\alpha)$  is a NCCW complex of dimension  $\max\{n, m + 1\}$ .*

*Proof.* By Propositions 3.7 and 3.8, the morphism  $p: \text{Cyl}(\alpha) \rightarrow B_m$  induced by  $\alpha$  is a cofibration with  $\text{Cone}(\alpha)$  as its kernel. So  $\text{Cone}(\alpha)$  is a cofiber for this cofibration. Also  $\text{Cone}(\alpha)$  satisfies the following pullback diagram

$$\begin{array}{ccc} \text{Cone}(\alpha) & \xrightarrow{\pi_2} & CB_m \\ \pi_1 \downarrow & & \downarrow \text{ev}(1) \\ A_n & \xrightarrow{\alpha} & B_m. \end{array}$$

where  $\pi_1$  and  $\pi_2$  are projections onto the first and second coordinates.

Since  $CB_m$  is a NCCW complex of dimension  $m + 1$ ,  $\text{ev}(1)$  and  $\alpha$  are simplicial morphisms in the pullback diagram for  $\text{Cone}(\alpha)$ , it follows from Remark 2.12 that  $\text{Cone}(\alpha)$  is a NCCW complex of dimension  $\max\{n, m + 1\}$ . □

**Remark 3.14.** Since  $CB \subset \mathbb{I}B$ , so for any  $*$ -morphism  $\alpha$ , we have the inclusion  $\text{Cone}(\alpha) \subset \text{Cyl}(\alpha)$ . Also for the zero morphism  $0: A \rightarrow B$ , we have

$$\begin{aligned} \text{Cone}(0) &= \{a \oplus f \in A \oplus CB : f(1) = 0\} = A \oplus C_0((0, 1) \rightarrow b) = A \oplus SB \\ \text{Cyl}(0) &= \{a \oplus f \in A \oplus \mathbb{I}B : f(1) = 0\} = A \oplus C_0([0, 1] \rightarrow B) \simeq A \oplus CB. \end{aligned}$$

**Proposition 3.15.** *For the morphism  $\alpha: A \rightarrow B$  between  $C^*$ -algebras,  $A$  is a retraction of  $\text{Cyl}(\alpha)$ .*

*Proof.* Let  $\pi: \text{Cyl}(\alpha) \rightarrow A$  be given by  $\pi(a \oplus f) := a$  and  $\eta: A \rightarrow \text{Cyl}(\alpha)$  by  $\eta(a) := a \oplus \alpha(a)$ , where  $\alpha(a)$  denotes the constant map  $t \mapsto \alpha(a)$ . Then  $\pi \circ \eta = \text{id}_A$ . Now let the homotopy  $\psi: \text{Cyl}(\alpha) \rightarrow \mathbb{I}\text{Cyl}(\alpha)$  be defined by

$$\psi(a \oplus f): \mathbb{I} \longrightarrow \text{Cyl}(\alpha), \quad t \longmapsto a \oplus f_t,$$

where  $f_t: \mathbb{I} \rightarrow B$  is defined as  $f_t(s) = f((1 - s)t + s)$  for each  $s \in \mathbb{I}$ . Then we can see that

$$\begin{aligned} \psi(a \oplus f)(0) &= a \oplus f = \text{id}_{\text{Cyl}(\alpha)}(a \oplus f) \\ \psi(a \oplus f)(1) &= a \oplus f(1) = a \oplus \alpha(a) = \eta \circ \pi(a \oplus f), \end{aligned}$$

and so  $\eta \circ \pi$  and  $\text{id}_{\text{Cyl}(\alpha)}$  are homotopic. □

## 4. NONCOMMUTATIVE MAPPING CYLINDRICAL AND CONICAL TELESCOPE

In this part we generalize the notions of noncommutative mapping cylinder and noncommutative mapping cone. Conditions for the existence of their NCCW complex structure are specified. It is seen that they provide examples of NCCW complex cofibers. Their topological properties are studied in detail.

**Definition 4.1.** For a sequence of length  $n$  of  $C^*$ -algebras

$$A_1 \xrightarrow{\alpha_1} A_2 \xrightarrow{\alpha_2} \cdots \xrightarrow{\alpha_{n-1}} A_n \xrightarrow{\alpha_n} A_{n+1},$$

the *NC mapping cylindrical telescope* is defined by

$$\begin{aligned} T_n &:= \{a \oplus f_2 \oplus \cdots \oplus f_{n+1} \in A_1 \oplus \mathbb{I}A_2 \oplus \cdots \oplus \mathbb{I}A_{n+1} : \\ &\quad f_{k+1}(1) = \alpha_k \circ \alpha_{k-1} \circ \cdots \circ \alpha_1(a), k = 1, 2, \dots, n\}. \end{aligned}$$

Since each  $\alpha_k$  is continuous,  $T_n$  is a closed subalgebra of the  $C^*$ -algebra  $A_1 \oplus \mathbb{I}A_2 \oplus \cdots \oplus \mathbb{I}A_{n+1}$ , and hence is itself a  $C^*$ -algebra. Also we note that for  $n = 1$ ,  $T_1 = \text{Cyl}(\alpha_1)$ .

**Proposition 4.2.** For each  $n \geq 2$ ,  $T_{n-1}$  is a retraction of  $T_n$ .

*Proof.* The proof is done by induction on  $n$ . For  $n = 1$ , let  $\beta_2: T_1 \rightarrow A_3$  be defined by  $\beta_2(a \oplus f_2) = \alpha_2 \circ \alpha_1(a)$ . Then  $\beta_2$  is a  $C^*$ -morphism and from Proposition 3.15,  $T_1$  is a retraction of  $\text{Cyl}(\beta_2)$ . But  $\text{Cyl}(\beta_2) = T_2$ , since

$$\begin{aligned} \text{Cyl}(\beta_2) &= \{(a \oplus f_2) \oplus f_3 \in T_1 \oplus \mathbb{I}A_3 : \beta_2(a \oplus f_2) = f_3(1)\} \\ &= \{a \oplus f_2 \oplus f_3 \in A_1 \oplus \mathbb{I}A_2 \oplus \mathbb{I}A_3 : f_2(1) = \alpha_1(a), f_3(1) = \alpha_2 \circ \alpha_1(a)\} \\ &= T_2. \end{aligned}$$

Now by induction, if we define  $\beta_n: T_{n-1} \rightarrow A_{n+1}$  by  $\beta_n(a \oplus f_2 \oplus \cdots \oplus f_n) = \alpha_n \circ \alpha_{n-1} \circ \cdots \circ \alpha_1(a)$ , we see that  $T_{n-1}$  is a retraction of  $T_n$ .  $\square$

**Corollary 4.3.** For the sequence of Definition 4.1,  $A_1$  is a retraction of  $T_n$ .

*Proof.* From the Proposition 4.2,  $T_n$  retracts to  $T_1 = \text{Cyl}(\alpha_1)$  and since by Proposition 3.15,  $\text{Cyl}(\alpha_1)$  retracts to  $A_1$ , so  $A_1$  is a retraction of  $T_n$ .  $\square$

**Corollary 4.4.** For the sequence of Definition 4.1,  $K_0(A_1) = K_0(T_1) = \cdots = K_0(T_n)$ .

**Proposition 4.5.** For the sequence of Definition 4.1, if  $\alpha_m \circ \alpha_{m-1} \circ \cdots \circ \alpha_{m-k} = 0$  for some  $k < m \leq n$ , then

$$T_n \simeq T_{m-1} \oplus \left( \bigoplus_{i=m+1}^{n+1} CA_i \right).$$

*Proof.*

$$\begin{aligned}
T_n &= \{a \oplus f_2 \oplus \cdots \oplus f_{n+1} \in A_1 \oplus \mathbb{I}A_2 \oplus \cdots \oplus \mathbb{I}A_{n+1} : \\
&\quad f_{k+1}(1) = \alpha_k \circ \alpha_{k-1} \circ \cdots \circ \alpha_1(a), \ k = 1, 2, \dots, n\} \\
&= \{a \oplus f_2 \oplus \cdots \oplus f_{n+1} \in A_1 \oplus \mathbb{I}A_2 \oplus \cdots \oplus \mathbb{I}A_{n+1} : \\
&\quad f_{k+1}(1) = \alpha_k \circ \alpha_{k-1} \circ \cdots \circ \alpha_1(a), \ 1 \leq k < m, \ f_{k+1}(1) = 0, \ m \leq k \leq n\} \\
&\simeq T_{m-1} \oplus CA_{m+1} \oplus \cdots \oplus CA_{n+1}.
\end{aligned}$$

□

**Corollary 4.6.** *For the exact sequence  $A_1 \xrightarrow{\alpha_1} A_2 \xrightarrow{\alpha_2} \cdots \xrightarrow{\alpha_{n-1}} A_n \xrightarrow{\alpha_n} A_{n+1}$  of length  $n$ ,  $T_n \simeq T_{n-1} \oplus CA_{n+1}$  and in particular,*

$$T_n \simeq \text{Cyl}(\alpha_1) \oplus \left( \bigoplus_{i=3}^{n+1} CA_i \right).$$

**Proposition 4.7.** *If  $A_1 \xrightarrow{\alpha_1} A_2 \xrightarrow{\alpha_2} \cdots \xrightarrow{\alpha_{n-1}} A_n \xrightarrow{\alpha_n} A_{n+1}$  is a sequence of simplicial morphisms between NCCW complexes of dimensions  $m_1, m_2, \dots, m_{n+1}$  then  $T_n$  is a NCCW complex of dimension  $\max\{m_1, 1 + m_2, 1 + m_3, \dots, 1 + m_{n+1}\}$ .*

*Proof.* Since  $\alpha_1: A_1 \rightarrow A_2$  is a simplicial morphism, by Proposition 3.8,  $T_1 = \text{Cyl}(\alpha_1)$  is a NCCW complex of dimension  $\max\{m_1, 1 + m_2\}$ . Let  $\beta_2: T_1 \rightarrow A_3$  be the \*-morphisms of Proposition 4.2. Since  $\alpha_1$  and  $\alpha_2$  are simplicial morphisms, then so is  $\beta_2$ , and  $T_2 = \text{Cyl}(\beta_2)$  is a NCCW complex of dimension  $\max\{\max\{m_1, 1 + m_2\}, 1 + m_3\} = \max\{m_1, 1 + m_2, 1 + m_3\}$ . Inductively, the morphism

$$\beta_n: T_{n-1} \longrightarrow A_{n+1}, \quad a \oplus f_2 \oplus \cdots \oplus f_n \longmapsto \alpha_n \circ \alpha_{n-1} \circ \cdots \circ \alpha_1(a)$$

is simplicial, and so  $T_n = \text{Cyl}(\beta_n)$  is a NCCW complex of dimension  $\max\{m_1, 1 + m_2, 1 + m_3, \dots, 1 + m_{n+1}\}$ . □

**Definition 4.8.** Let  $A_1 \xrightarrow{\alpha_1} A_2 \xrightarrow{\alpha_2} \cdots \xrightarrow{\alpha_{n-1}} A_n \xrightarrow{\alpha_n} A_{n+1}$  be a sequence of morphisms between C\*-algebras. The *NC mapping conical telescope* is defined as

$$\begin{aligned}
T_n C &:= \{a \oplus f_2 \oplus \cdots \oplus f_{n+1} \in A_1 \oplus CA_2 \oplus \cdots \oplus CA_{n+1} : \\
&\quad f_{k+1}(1) = \alpha_k \circ \alpha_{k-1} \circ \cdots \circ \alpha_1(a), \ k = 1, 2, \dots, n\}.
\end{aligned}$$

As in the case  $T_n$ , for  $n = 1$ ,  $T_1 C = \text{Cone}(\alpha_1)$ .

**Proposition 4.9.** *For the sequence of Definition 4.1, if  $\alpha_m \circ \alpha_{m-1} \circ \cdots \circ \alpha_{m-k} = 0$  for some  $k < m \leq n$ , then*

$$T_n C = T_{m-1} C \oplus \left( \bigoplus_{i=m+1}^{n+1} SA_i \right).$$

*Proof.*

$$\begin{aligned}
T_n C &= \{a \oplus f_2 \oplus \cdots \oplus f_{n+1} \in A_1 \oplus CA_2 \oplus \cdots \oplus CA_{n+1} : \\
&\quad f_{k+1}(1) = \alpha_k \circ \alpha_{k-1} \circ \cdots \circ \alpha_1(a), \ k = 1, 2, \dots, n\} \\
&= \{a \oplus f_2 \oplus \cdots \oplus f_{n+1} \in A_1 \oplus CA_2 \oplus \cdots \oplus CA_{n+1} : \\
&\quad f_{k+1}(1) = \alpha_k \circ \alpha_{k-1} \circ \cdots \circ \alpha_1(a), \ 1 \leq k < m, \ f_{k+1}(1) = 0, \ m \leq k \leq m\} \\
&= T_{m-1} C \oplus SA_{m+1} \oplus \cdots \oplus SA_{n+1}.
\end{aligned}$$

□

**Corollary 4.10.** *If the sequence of definition 4.1 is exact, then  $T_n C = T_{n-1} \oplus SA_{n+1}$ , and in particular,*

$$T_n C = \text{Cone}(\alpha_1) \oplus \left( \bigoplus_{i=3}^{n+1} SA_i \right).$$

**Proposition 4.11.** *For each sequence of length  $n > 1$ , there is an exact sequence*

$$0 \longrightarrow SA_{n+1} \longrightarrow T_n C \longrightarrow T_{n-1} \longrightarrow 0$$

*Proof.* Let  $i: SA_{n+1} \rightarrow T_n C$  be the inclusion morphism  $f \mapsto 0 \oplus 0 \oplus \cdots \oplus f$  and  $\pi: T_n C \rightarrow T_{n-1} C$  be the projection  $a \oplus f_2 \oplus \cdots \oplus f_{n+1} \mapsto a \oplus f_2 \oplus \cdots \oplus f_n$ , then  $\ker \pi = i(SA_{n+1})$ . □

**Proposition 4.12.** *For each sequence of length  $n$ , there exists an exact sequence*

$$0 \longrightarrow T_n C \longrightarrow T_n \longrightarrow \bigoplus_{k=2}^{n+1} A_k \longrightarrow 0.$$

*Proof.* Let  $i: T_n C \rightarrow T_n$  be the obvious inclusion and  $p: T_n \rightarrow \bigoplus_{k=2}^{n+1} A_k$  be defined by  $p(a \oplus f_2 \oplus \cdots \oplus f_{n+1}) := f_2(0) \oplus \cdots \oplus f_{n+1}(0)$ . Then  $\ker p = T_n C$ . □

**Proposition 4.13.** *Let*

$$(4.1) \quad A_1 \xrightarrow{\alpha_1} A_2 \xrightarrow{\alpha_2} \cdots \xrightarrow{\alpha_{n-1}} A_n \xrightarrow{\alpha_n} A_{n+1}$$

*be an arbitrary sequence of length  $n$  of  $C^*$ -algebras, then:*

- *All the morphisms*

$$p_j: T_n \rightarrow A_j, \quad p_j(a \oplus f_2 \oplus \cdots \oplus f_{n+1}) = f_j(0)$$

*for  $j = 2, \dots, n+1$  are cofibrations.*

- *The morphism  $p: T_n \rightarrow A_2 \oplus \cdots \oplus A_{n+1}$  defined by*

$$p(a \oplus f_2 \oplus \cdots \oplus f_{n+1}) = (f_2(0) \oplus \cdots \oplus f_{n+1}(0))$$

*is a cofibration.*

- *$T_n C$  is a cofiber of the cofibration  $p$ .*

*Proof.* Fix  $j$ . Let a homotopy  $G: D \rightarrow \mathbb{I}A_j$  and a lift  $g_0: D \rightarrow T_n$ , of  $G$  at zero be given. So  $p_j g_0(d) = G(d)(0)$  for  $d \in D$ . Write  $g_0(d) = (a \oplus f_2 \oplus \dots \oplus f_{n+1})$  so that for  $k = 1, 2, \dots, n$ ,

$$f_{k+1}(1) = \alpha_k \circ \alpha_{k-1} \circ \dots \circ \alpha_1(a).$$

From the lifting property of  $g_0$ ,  $f_j(0) = G(d)(0)$ . Let the lift  $H: D \rightarrow \mathbb{I}T_n$  for  $G$ , be defined by

$$H(d)(t) = (a \oplus k_{2,t} \oplus \dots \oplus k_{n+1,t}).$$

To fulfil the homotopy lifting properties  $H$  must satisfy

- $p_j(H(d)(t)) = G(d)(t)$  for  $d \in D$  and  $t \in \mathbb{I}$ , i.e.,  $k_{j,t}(0) = G(d)(t)$ .
- $H(d)(0) = g_0(d)$ , i.e.,  $k_{i,0} = f_i$  for  $i = 2, \dots, n+1$ .

To complete the definition of the homotopy  $H$ , for  $i = 2, \dots, n+1$ , set

$$k_{i,t}(s) = \begin{cases} G(d)(t-2s) & 0 \leq s \leq \frac{t}{2} \\ f_i\left(\frac{2s-t}{2-t}\right) & \frac{t}{2} \leq s \leq 1 \end{cases}$$

for  $s \in \mathbb{I}$ .

So  $p_j$ s are cofibrations. This completes the first part of the proposition.

For the second part as in part one, let

$$\mathcal{G}: D \rightarrow \mathbb{I}(A_2 \oplus \dots \oplus A_{n+1})$$

be a homotopy with  $\hat{g}_0: D \rightarrow T_n$  as its lift at zero. Define the homotopy

$$\mathcal{H}: D \rightarrow \mathbb{I}T_n, \quad \mathcal{H}(d)(t) = (a \oplus k_{2,t} \oplus \dots \oplus k_{n+1,t})$$

where

$$\hat{g}_0(d) = (a \oplus f_2 \oplus \dots \oplus f_{n+1})$$

and for  $k = 1, 2, \dots, n$ ,

$$f_{k+1}(1) = \alpha_k \circ \alpha_{k-1} \circ \dots \circ \alpha_1(a).$$

Let  $\mathcal{G}(d)(t) = (g_{2,t} \oplus \dots \oplus g_{n+1,t})$ . For  $i = 2, \dots, n+1$ , define

$$k_{i,t}(s) = \begin{cases} g_{i,t}(t-2s) & 0 \leq s \leq \frac{t}{2} \\ f_i\left(\frac{2s-t}{2-t}\right) & \frac{t}{2} \leq s \leq 1. \end{cases}$$

Then  $\mathcal{H}$  satisfies the properties of the homotopy lift for  $\mathcal{G}$ .

The third part of the proposition follows from the fact that the mapping conical telescope  $T_n C$  is the kernel of the cofibration  $p$ . So it is a cofiber by definition.  $\square$

The following proposition studies the K-theoretic behaviour of mapping cylindrical and conical telescope. For more details on K-theory and  $C^*$ -algebras, we refer to [15].

**Proposition 4.14.** *For each sequence of length  $n$ , there exists a cyclic six term exact Sequence,*

$$\begin{array}{ccccc} K_0(T_n C) & \longrightarrow & K_0(T_n) & \longrightarrow & \bigoplus_{i=2}^{n+1} K_0(A_i) \\ \uparrow & & & & \downarrow \\ \bigoplus_{i=2}^{n+1} K_1(A_i) & \longleftarrow & K_1(T_n) & \longleftarrow & K_1(T_n C). \end{array}$$

*Proof.* Since  $T_n C$  is an ideal in  $T_n$ ,  $T_n/T_n C = \bigoplus_{i=2}^{n+1} A_i$ ,  $K_0(\bigoplus_{i=2}^{n+1} A_i) = \bigoplus_{i=2}^{n+1} K_0(A_i)$  and  $K_1(\bigoplus_{i=2}^{n+1} A_i) = \bigoplus_{i=2}^{n+1} K_1(A_i)$ , the exactness of the six term sequence follows from [15, 9.3.2].  $\square$

**Proposition 4.15.** *If  $A_1 \xrightarrow{\alpha_1} A_2 \xrightarrow{\alpha_2} \dots \xrightarrow{\alpha_{n-1}} A_n \xrightarrow{\alpha_n} A_{n+1}$  is a sequence of simplicial morphisms between NCCW complexes of dimensions  $m_1, m_2, \dots, m_{n+1}$ , then  $T_n C$  is a NCCW complex of dimension  $\max\{m_1, 1+m_2, 1+m_3, \dots, 1+m_{n+1}\}$ .*

*Proof.* Since  $\alpha_1: A_1 \rightarrow A_2$  is a simplicial morphism, by Proposition 3.13,  $T_1 C = \text{Cone}(\alpha_1)$  is a NCCW complex of dimension  $\max\{m_1, 1+m_2\}$ . Let  $\beta_2: T_1 C \rightarrow A_3$  be defined as  $\beta(a \oplus f_2) = \alpha_2 \circ \alpha_1(a)$ . Since  $\alpha_1$  and  $\alpha_2$  are simplicial morphisms, then so is  $\beta_2$ , and  $T_2 C = \text{Cone}(\beta_2)$  is a NCCW complex of dimension  $\max\{m_1, 1+m_2, 1+m_3\} = \max\{m_1, 1+m_2, 1+m_3\}$ . Inductively, the morphism

$$\beta_n: T_{n-1} C \longrightarrow A_{n+1}, \quad a \oplus f_2 \oplus \dots \oplus f_n \mapsto \alpha_n \circ \alpha_{n-1} \circ \dots \circ \alpha_1(a)$$

is simplicial, and so  $T_n C = \text{Cone}(\beta_n)$  is a NCCW complex of dimension  $\max\{m_1, 1+m_2, 1+m_3, \dots, 1+m_{n+1}\}$ .  $\square$

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